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Design of infrared surface plasmon resonance sensors based on graphene ribbon arrays

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ABSTRACT

A surface plasmon resonance (SPR) based graphene sensor for infrared wavelength is presented. It consists of a graphene ribbon array on top of a quartz substrate. The refractive index changes above the sensor surface, which is due to the appearance of gas or the absorption of biomolecules, can be detected by measuring the resulting spectral shifts of the resonant transmission dip. The dynamic tunability of graphene enables the detectable refractive index changes covering a broadband wavelength range. The influence of Fermi level and the number of graphene layers on the performance of sensor are investigated in details, which should be useful for guiding the design of sensors based on a graphene ribbon array. The sensor can be used for sensing both gas and low-refractive-index materials in an aqueous environment.

1. Introduction

Surface plasmons (SPs) are perpendicularly confined electromagnetic surface waves which can exist at dielectric–metal interfaces [1]. Surface plasmon resonance (SPR), which based on the excitation of SPs, has been widely used in a variety of sensing application, since it is highly sensitive to the environmental refractive index variations [2–4]. The basic principle is: in the sensing medium, a little change in the refractive index due to the appearance of gas or the absorption of biomolecules, will lead to a significant change in wave vector of SPPs, which can be measured by the resulting spectral shifts of the resonant transmission dip.

Conventional SPR sensors, which are based on a flat dielectric-metal configuration, have been mainly used for sensing with visible and near-infrared wavelength. However, for mid- and far-infrared frequencies, the SPRs are weakly confined on the metallic–dielectric interface, which leads to a limited sensitivity [5]. In order to overcome this problem, mid-infrared sensors based on graphene ribbon array are proposed [5,6].

Graphene, a two dimensional layer of carbon atoms arranged in a honeycomb lattice, has attracted significant attention since its experimental discovery [7–9]. It has been theoretically investigated and experimentally demonstrated that graphene can be used for exciting and propagating surface plasmons [10,11]. Due to its unique electric, mechanical and thermal properties, graphene has found applications in a very wide area, such as active plasmonic switch [12], perfect absorber [13,14], photodetectors [15], sensors [5] and plasmon waveguiding [16]. One of the promising points of graphene is that it's conductivity can be dynamically tuned for a wide wavelength range from infrared to THz by use of chemical or electrostatic gatings [17], which makes it a promising platform to design highly tunable active plasmonic devices. Moreover, graphene surface plasmons (GSPs) allows for an extremely strong confinement of fields to the interface, which makes it a platform for light–matter interactions [10,16].

At present, there are some studies about graphene sensing [18–22]. However, the graphene has only been used as an auxiliary component of metallic nanostructures. Until recently, Vasic et al. theoretically investigated a possible utilization of graphene ribbon arrays for sensing the index change of dielectric environment, in which graphene surface plasmons is exploited to sense of pure dielectric as well as dispersive films with vibrational modes [5]. However, the out coupling efficiency of their device, i.e. the reflection efficiency, is very small (<0.16) [5]. Zhao et al. proposed an infrared graphene plasmonic transmission-type biosensor, and investigates the influence of dielectric constants of substrates, Fermi levels and structure parameters on the sensitivity and accuracy [6].

In this work, we design a novel transmission-type SPR sensor based on graphene nano-ribbon array for the infrared wavelength. The numerical simulations are based on rigorous coupled-wave analysis (RCWA) [23,24]. The fundamental principles of sensor, which based on the SPR of graphene ribbon, are investigated first. The bulk refractive index sensitivity and figure of merit (FOM) for transmission-type sensor are proposed to evaluate the overall

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performance of the sensor. The effects of Fermi level and the number of graphene layers on the performance of sensor are studied in details, which should be useful for guiding the design of sensors based on a graphene ribbon array. The designed sensor can be used for sensing both gas and low-refractive-index materials in an aqueous environment.

2. Principles of graphene ribbon arrays based sensor

The structure of a transmission-type sensor based on graphene ribbon array is shown in Fig. 1. It consists of a graphene nano-ribbon array on top of a dielectric substrate. n_1 is the refractive indexes of mediums above the graphene, which changes according to different sensing medium. The material of substrate is quart (SiO_2) with refractive index of n_s=1.45. ε_g is the relative permittivity of graphene. d is the period of graphene nano-ribbon. h is the thickness of graphene.

Graphene is modelled as an anisotropic material. At room temperature $T=300$ K and for mid- and far-infrared frequencies $\hbar\omega < 2E_f$, the optical conductivity of graphene can be approximated by a Drude model [25,26]:

$$\sigma(\omega)=\frac{e^2E_f}{\pi\hbar^2}\frac{i}{\omega+i\tau^{-1}} \tag{1}$$

where $\hbar$ is the reduced Planck's constant and E_f is the energy of Fermi level, ω is the angular frequency, e is the elementary charge, τ is the carrier relaxation lifetime.

In the simulation, the graphene is modeled as a thin layer of thickness $h=0.34$ nm with the in-plane permittivity

$$\varepsilon_g=1+\frac{i\sigma(\omega)}{\varepsilon_0\omega h} \tag{2}$$

where ε_o is the relative permittivity of vacuum.

We consider the case of normal incidence and TM polarization (the magnetic field is in y direction). The dispersion relation of TM modes is [27]:

$$\frac{\varepsilon_1}{\sqrt{k_{SPP}^2-(\varepsilon_1\omega^2/c^2)}}+\frac{\varepsilon_S}{\sqrt{k_{SPP}^2-(\varepsilon_S\omega^2/c^2)}}=\frac{\sigma(\omega)}{i\omega\varepsilon_0} \tag{3}$$

where $\varepsilon_1={n_1}^2$ and $\varepsilon_s={n_s}^2$, c is velocity of light in vacuum, k_{SPP} is the wave vector of SPPs in graphene. Since $k_0=\omega/c \ll k_{SPP}$, the dispersion relation can be approximated as [10,27]:

$$k_{SPP}=\varepsilon_0\frac{\varepsilon_1+\varepsilon_S}{2}\frac{2i\omega}{\sigma(\omega)}=i\varepsilon_0\frac{\varepsilon_1+\varepsilon_S}{\sigma(\omega)}k_0c=i\varepsilon_0\frac{\varepsilon_1+\varepsilon_S}{\sigma(\omega)}\frac{2\pi}{\lambda_{SPP}}c \tag{4}$$

Under normal incidence, the match condition of wave vector is expressed as:

$$\mathrm{Re}(k_{SPP})=\mathrm{Re}\left(i\varepsilon_0\frac{\varepsilon_1+\varepsilon_S}{\sigma(\omega)}\frac{2\pi}{\lambda_{SPP}}c\right)=m\frac{2\pi}{d} \tag{5}$$

where m is an integer represent the diffraction order of graphene ribbon arrays, Re stands for the real part of a wave vector. Thus, the wavelength of SPP can be approximately expressed as:

$$\lambda_{SPP}=\frac{\pi\hbar c}{e}\sqrt{\frac{2(n_1^2+n_S^2)\varepsilon_0 d}{E_F m}} \tag{6}$$

It should be noted that, Eq. (6) is an approximate expression due to the neglecting imaginary part of wave vector. Therefore, there are certain differences between the resonant wavelength obtained by theoretical expression and numerical simulation. However, Eq. (6) can still give a qualitative prediction of resonant wavelength variation when the parameters change.

At the SPR condition, when the refractive index of the sensing medium is changed by δn_1, the resonant wavelength shifts by $\delta\lambda_{SPP}$, thus the bulk refractive index sensitivity of the sensor based on a graphene nano-ribbon array is defined as the ratio of $\delta\lambda_{SPP}$ to δn_1:

$$S_\lambda=\frac{\delta\lambda_{SPP}}{\delta n_1}=\frac{\pi\hbar c}{e}\sqrt{\frac{2\varepsilon_0 d}{E_F m}}\frac{n_1}{\sqrt{(n_1^2+n_S^2)}} \tag{7}$$

The unit for S_λ is nanometer per refractive index unit (RIU). When the duty cycle of graphene ribbon array $f=w/d=1/2$, the Eq. (7) can also be expressed by:

$$S_\lambda=\frac{2\pi\hbar c}{e}\sqrt{\frac{\varepsilon_0 w}{E_F m}}\frac{n_1}{\sqrt{(n_1^2+n_S^2)}} \tag{8}$$

Since the sensor is a transmission-type configuration, in order to compare the overall performance of the sensor, the figure of merit (FOM) is defined as follows:

$$\mathrm{FOM}=\frac{S_\lambda}{\mathrm{FWHM}}\Delta T \tag{9}$$

where FWHM is the full width at half maximum of an SPR dip, and $\Delta T=1-T_{min}$ means the transmittance change of the resonant dip, T_{min} is the transmittance at resonant wavelength.

3. Results and discussions

The structure parameters of the designed sensor are as follows: d=250 nm, f=0.5, h=0.34 nm, n_s=1.45. The initial Fermi level is selected as E_f=0.25 eV and the carrier relaxation time is τ=0.3 ps. In this work, the graphene surface plasmon dips are excited by +1 diffraction order, so m=1. Typically, for sensing of gas, such the hydrogen, the refractive index changes from 1 to 1.05, and for sensing of low-refractive-index materials in an aqueous environment, the refractive index changes from 1.30 to 1.35.

The transmission spectra of the designed sensor with the environment refractive index changes mentioned above are shown in Fig. 2(a) and (b), respectively. As can be seen from Fig. 2(a), when the refractive index changes from 1.0 to 1.05, the resonant wavelength shifts about 236 nm. The average FWHM is about 538.3 nm,

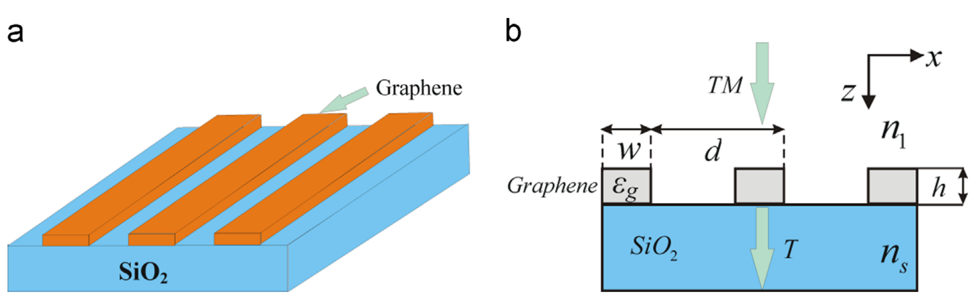

Fig. 1. (a) Schematic of the graphene ribbon-based sensor. (b) The basic parameters and nomenclature of the sensor.